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Reservoir reconstruction technologies for coalbed methane recovery in deep and multiple seams

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ABSTRACT

Multiple coal seams widely develop in the deep Chinese coal-bearing strata. Ground in situ stress and coal seam gas pressure increase continuously with the increase of the mining depth, and coal and gas outburst disasters become increasingly severe. When the coal is very deep, the gas content and pressure will elevate and thus coal seams tends to outburst-prone seams. The safety and economics of exploited first-mined coal seams are tremendously restricted. Meanwhile, the multiple seams occurrence conditions resulted in different methane pressure systems in the coal-bearing strata, which made the reservoir reconstruction of coal difficult. Given the characteristics of low saturation, low permeability, strong anisotropy and soft coal of Chinese coal seams, a single hydraulic fracturing surface well for reservoir reconstruction to pre-drain the coalbed methane (CBM) of multiple seams concurrently under the different gas pressure systems has not yet gained any breakthroughs. Based on analyses of the main features of deep CBM reservoirs in China, current gas control methods and the existing challenges in deep and multiple seams, we proposed a new technology for deep CBM reservoir reconstruction to realize simultaneous high-efficiency coal mining and gas extraction. In particular, we determined the first-mined seam according to the principles of effectiveness and economics, and used hydraulic fracturing surface well to reconstruct the first-mined seam which enlarges the selection range of the first-mined seam. During the process of mining first-mined seam, adjacent coal seams could be reconstructed under the mining effect which promoted high-efficiency pressure relief gas extraction by using spatial and comprehensive gas drainage methods (combination of underground and ground CBM extraction methods). A typical integrated reservoir reconstruction technology, "One well for triple use", was detailed introduced and successfully applied in the Luling coal mine. The application showed that the proposed technology could effectively promote coal mining safety and simultaneously high-efficiency gas extraction.

1. Introduction

Coal, as the primary energy source, accounts for 70% of the China's total energy supply and more than 48% of the world's coal consumption. The annual coal production in China has increased significantly from 1299 million metric tons (Mt) in 2000 to 3870 Mt in 2014 and this makes China as the largest coal-producing country in the world. It is envisioned that coal will continuously play a leading role in the Chinese energy mix in next a few decades. With the rapid sustainable development of Chinese economy and the continuous demand and dependence on coal production, the geology and technical conditions for coal exploitation are deteriorating [1]. With excessive coal mining depth increase, both gas pressure and content in deep coal seams continue to increase along with much more complex coal geologic structures. The gas related mine geo-hazards, particularly coal and gas outburst disasters, are becoming increasingly severe. Currently, more than 1000 coal mines have been classified to be outburst risk mines, and annually there were more than 300 fatalities directly due to outbursts in China [2]. Coal seam gas has become the key factor that constrains safe and efficient production of Chinese deep coal mines [3,4].

As a by-product of coal production, coalbed methane (CBM) is not only a major hazard of coal mine production but also a clean

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and efficient energy resource [5], and an intense greenhouse gas with a Global Warming Potential (GWP) of 25, i.e., 25 times the environmental impact of carbon dioxide [6]. The energy released in the combustion of 1 m^3/t methane is 35.9 MJ, equivalent to the combustion of 1.2 kg of standard coal [3,5]. As the geological resources of CBM at above 2000 m depth in China amount to 36.81 trillion m^3, which ranks 3rd in the world, therefore, measures to control coal mine methane (CMM) in China bear the multiple purposes of promoting mining safety, recovering methane resources and abating greenhouse gas emissions [3,6].

China's known coal reserves amount to 5.57 trillion metric tons, 63% of which is occurred at a depth of 800–2000 m, with coal reserves of 3.25 trillion metric tons. In addition, 70% of Chinese coal reserves are multiple seams [7], as summarized in Table 1. Coal is a self-sourced reservoir rock, which is always referred as a CBM reservoir in areas for oil-gas exploitation [8,9]. And the multiple-seam coal regions are usually rich in CBM resources in China and present a good development prospect for CBM production [10].

In order to guarantee the safe and efficient exploitation of coal resources, CBM extraction should be initially conducted before the actual mining to reduce the overall gas content and to mitigate the gas-related mining hazards [11,12]. However, the Chinese deep coal reservoirs share the common characteristics with low permeability, low saturation, under pressure and strong anisotropy [13,14]. The pre-mining degasification and gas drainage in the deep coal seams is technically challenging, therefore, CBM reservoir stimulation emphasizing on the permeability enhancement is required for the mine degasification and for the methane energy recovery as well [15,16].

Based on the unique features of deep coal seams, the current coal gas extraction technologies were summarized and reviewed in the article and the existing challenges for each technology were also analyzed. In order to effectively drain the gas from multiple coal seams, a new CBM reservoir stimulation to enhance the permeability was proposed by stress-relief and/or unloading fracturing through adjacent seam mining. This new technology has been implemented in a deep gas mine and it was proven to be very effective to ensure gas hazard mitigation with additional benefit of gas energy recovery. A case study was finally provided and outcomes were summarized and analyzed for Luling coal mine in China.

2. Main features of deep CBM reservoirs in China

Most Chinese coal originated during the Carboniferous-Permian [6,17]. Thereafter, the coal underwent a number of strong tectonic movements that destroyed the original fracture/cleat networks in the coal seams. As a result, the coal became structurally complicated, high degree of metamorphism, mechanically soft, and very low gas deliverability due to low reservoir permeability. Table 2 summarizes the virgin coal seam reservoir properties for the Chinese, US and Australian CBM reservoirs. The permeability of Chinese coal is usually on the magnitude of 10^{-4}–10^{-3} mD except for Jincheng coal field. As comparison, permeability of San Juan coal in US is four orders of magnitude higher than most Chinese coals and Bowen basin coal in Australia is three order of magnitude higher than most Chines coals. This explained why the San Juan and Bowen coals are very successful in CBM production and commercialization. Although CBM extraction has a long history in China, it is still not yet up to the expected commercialization level. Therefore, tax incentives is being distributed in major CBM states in China. Currently, coal mine gas pre-drainage techniques face many challenges for large scale commercial production and thus the advanced reservoir stimulation technologies are required to increase the gas drainage efficiency [18,19].

Table 1
Coal seam groups occurrence of partial mines in China [6].

Coalfield	Coal seam conditions
Huainan	Seam C14, C13, B11b, B10, B8, B7a, B6, B5, B4, A3 and A1
Huaibei	Seam 4, 5, 6, 7, 8, 9, 10
Shenyang	Seam 7, 11, 12, 13
Yangquan	Seam 2, 3, 6, 8, 9, 12, 15
Pingdingshan	Seam 14, 15, 16, 17
Yaojie	Seam 1, 2, 3
Hedong	Seam 2, 3, 4, 5
Xishan	Seam 02, 03, 2, 4, 6, 7, 8, 9
Tiefa	Seam 12, 13, 14, 15, 16, 17
Laochang	Seam C2, C3, C4, C7 + 8, C8, C9, C13, C16, C19

Table 2
CBM reservoir property comparison for Chinese, US and Australian coal seams.

Coalfield	Virgin coal reservoir properties		
	Permeability (mD)	Gas pressure (MPa)	Gas content (m^3/t)
Huainan	0.00028	6.5	10–40
Huaibei	0.00121	5.1	10–35
Tianfu	0.00106	13.6	10–40
Yangquan	0.00037	2.3	10–40
Zhenzhou	0.00118	2.6	8–20
Shenyang	0.00035	8.3	10–35
Yaojie	0.00244	7.3	10–30
Jincheng	1.55	1.25	5–50
USA (San Juan)	10–100	–	9–19
Australia (Bowen)	1–10	–	8–17

Note: The CBM parameters in the table were measured or calculated in the current mining condition.

The China national coal mining depth is going deeper and deeper as the average annual rate of 10–50 m [20]. The mining depth of many coal mines in Mid-East of China has reached 800–1200 m below surface (e.g. 800 m in Huaibei, 850 m in Huainan, and 1000 m in Xuzhou). At these mining depths, the coal seam overburden stress ranges from 22 to 33 MPa and the coal seam gas pressure and gas content can exceed 6 MPa and 20 m^3/t respectively. Most of these coal seams have the virgin permeability at order of 0.001 mD or even lower, which makes CBM extraction inefficient and even not possible without secondary reservoir stimulation.

Surface borehole gas drainage is widely used as a conventional CBM extraction technology in today's world [19,21–23]. However, low virgin coal permeability limits the efficiency of the primary reservoir depletion at which the borehole drainage area/volume is very constrained. Meanwhile, deep Chinese coal exhibits a strong anisotropy of permeability which will further decrease the depletion efficiency for any given well patterns. Additionally, the Chinese main geological CBM accumulations are generally located in the Carboniferous-Permian coal-bearing regions where the coal ranks are known to be partially high due to the metamorphic effect. CBM resources in high rank coals account for >27.6% of the total resources, which owns the features of low permeability and difficulty in desorption, limiting the application of conventional CBM extraction technology [6]. In contrast, US high gas bearing coal seams are mainly distributed in the Cretaceous laver with thick coal seams, and rich-gas coalfields are often formed with high to low volatile bituminous coals associated with high reservoir pressure and high permeability, making larger production from a single surface well [24].

In Chinese coal mines, the coal-bearing strata develop into multiple and relatively stable low-permeability compartments, which serve as seals to prevent the vertical reservoir fluid exchange. Coal